CHARACTERIZATION OF THE PROPERTIES OF NON –COKING COALS AND THEIR CHARS

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology
In

METALLURGICAL AND MATERIALS ENGINEERING

By

RAVINDRA KUMAR SAHU

Roll No-214MM1554

Department of Metallurgical and Materials Engineering

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Under the Guidance of

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CERTIFICATE

This is to certify that the Thesis Report entitled "CHARACTERIZATION OF THE PROPERTIES OF NON–COKING COALS AND THEIR CHARS" submitted by RAVINDRA KUMAR SAHU bearing Roll no. 214MM1554 in partial fulfilment of the requirements for the award of Master of Technology in "METALLURGICAL AND MATERIALS ENGINEERING" at National Institute of Technology, Rourkela is an authentic work performed by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or diploma.

Date:
Place: Rourkela

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ABSTRACT

India has fifth largest coal reserve in the world but has a very limited reserve of coking coal which is the key material for the production of steel. Coking coal accounts for only 15% of the total reserve of India while non-coking coal accounts for 85%. Since India has an abundance of non-coking coal and scarcity of coking coal, there is a need to maximize the utilization of non-coking coal in various sectors such as power generation, steel industry, and cement industry. The current project has been taken up to contribute towards the potential growth of non-coking coal and their utilization in the steel sector in sponge iron making process. Non-coking coal is exploited in sponge iron making through direct reduction of iron ore commonly known as DRI method.

In the present project work different non-coking coal samples obtained from various coal mines of India namely South East Coalfields Limited (Chhattisgarh), Jindal coalfield (Chhattisgarh), Mahanadi Coalfields Limited Basundhara (Orissa), Gopalpur (Chattisgarh) and Asansol and Lingaraj coal mines. The project was undertaken with the following objectives: (i) Characterization of the selected coals for their chemical and physical properties, (ii) preparation of coal chars, and (iii) characterization of the chemical and physical properties of these coal chars. The coal and char samples were characterized for chemical properties (proximate analysis and ultimate analysis, calorific value) and physical properties (apparent porosity and density, caking index). The result was found that Basundhara (MCL) coals have highest fixed carbon content and calorific value. The reactivity of char produced at carbonization temperature 950°C towards carbon dioxide was measured, and value was found greater than 2gm/cc/sec which is desired in sponge iron plant. Effect of carbonization at different temperature (400°C, 600°C, 800°C and 950°C) on properties of coal char was investigated, and it was found that energy value and fixed carbon content and apparent density increases, whereas porosity decreases with the increase in carbonization temperature. Ash fusion temperature of some of the coal ashes was determined and found that these coal ashes have sufficient high ash fusion temperature to avoid ring formation. Results obtained from all the experiments conclude that most of the selected coals are suitable for sponge iron making.

Keywords: Non-coking coal, proximate analysis, ultimate analysis, calorific value, fixed carbon content, reactivity, ash fusion temperature, porosity, density, carbonization.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Three- quarters of Indian energy demand is met my fossil fuel. Coal is the most plentiful domestic fossil fuel resource. It is the backbone of Indian Power sector accounting for over 70% of generation, and it is the most abundant fossil fuel resource [1].India Accounts for about 7.0 % of Global Reserves. Of the total reserves of 293 Bte as on 31.03.12 in India, proved reserves were 40 percent and inferred and indicated reserves were 49 % and 11 % respectively. Out of Total reserve, 88% of the reserves (260BT) is estimated to comprise of non-coking coal with the balance being of the medium, prime and bendable coking-grade coal [2]. In other words regarding natural endowment, India has a significant reserve of non-coking coal, but the reserves of coking coal are very limited. So there is a need to maximize utilization of non-coking coal and its potential.

Coal is an essential input in the production of steel. The Indian steel industry has been facing acute shortage of coal for the last several years. India has seen an enormous rise in demand for steel for past few years. The steel production by 2016-17 is projected to be 105 MT. The corresponding requirement of coking coal for this quantity of steel is worked out at 67.2 MT in 2016-17 [3].

Primary steelmaking process involves blast furnace route which requires coking coal. However, India has a very limited reserve of coking coal while it has abundance of low-grade non-coking coal. More attention is being paid in recent years towards utilization of low-grade coal in Steel & Iron Industry with direct reduction process. This process has proved more economic viability by its ability to generate a considerable amount of electricity through the use of hot waste gas and char. Coal based direct reduction process have proved as the potential alternative route of iron making in India.

1.2 State Wise Coal Reserve in India

The details of state-wise geological resources of Coal are given as under [4].

Table 1.1: State wise coal reserves in India (In Million Tons)

State	Proved	Indicated	Inferred	Total
West Bengal	13404	13023	4894	31319
Jharkhand	41378	32781	6560	80717
Bihar	0	0	161	160
Madhya Pradesh	10411	12383	2880	25674
Chhattisgarh	16053	33254	3229	52532
Uttar Pradesh	885	179	0	1063
Maharashtra	5668	3187	2111	10965
Odisha	27792	37874	9409	75074
Andhra Pradesh	9728	9671	3069	22469
Assam	466	48	4	516
Sikkim	0	59	44	102
Arunachal Pradesh	32	41	20	91
Meghalaya	88	18	472	577
Nagaland	8	0	308	316
Total	**125916**	**142518**	**33161**	**301576**

(Source: Geological Survey of India)

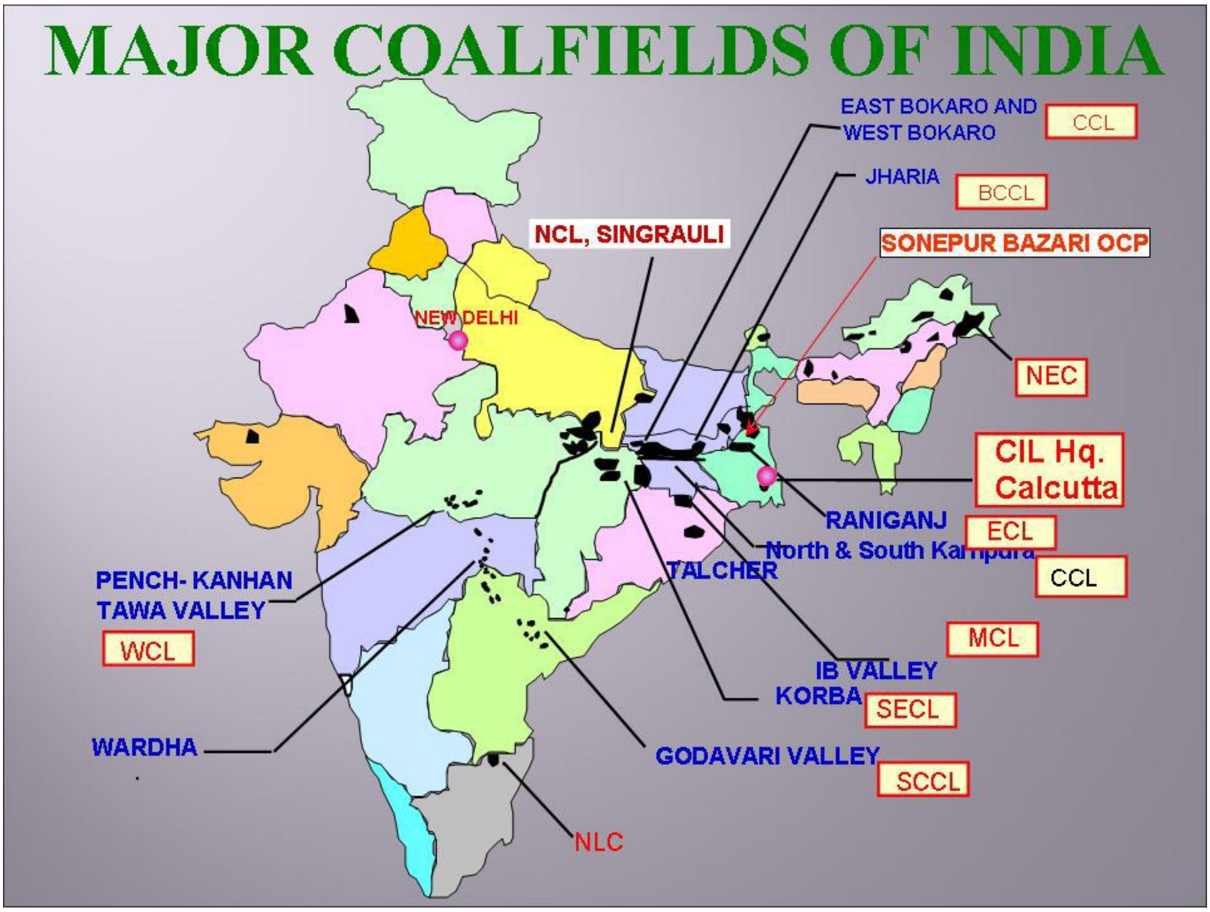
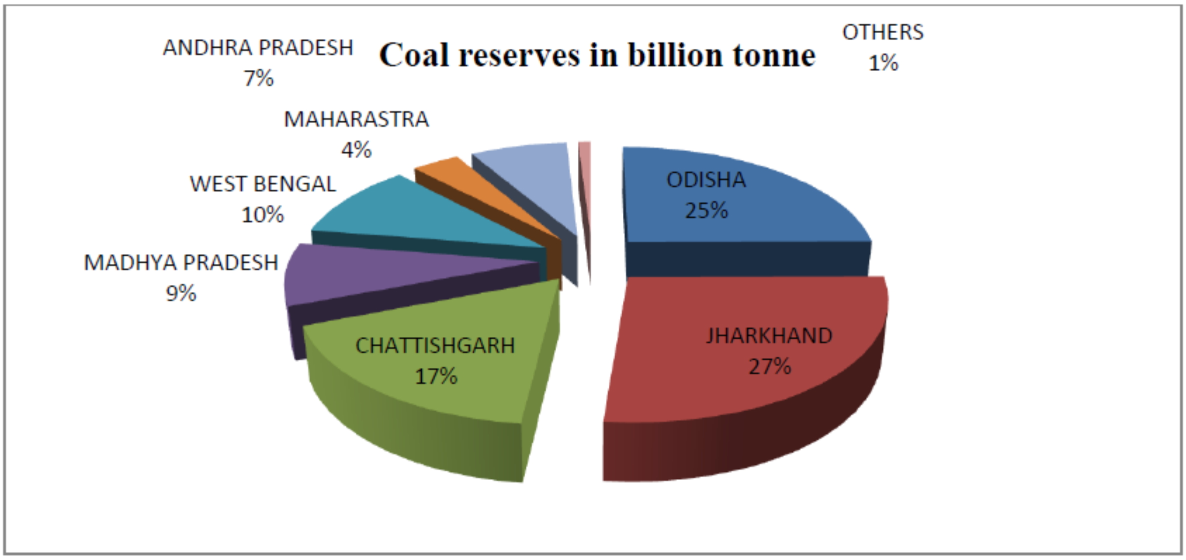


Fig. 1.1: Major coalfields of India (Source: Energy Statistics 2015)



(Source: Coal directory of India 2013-14)

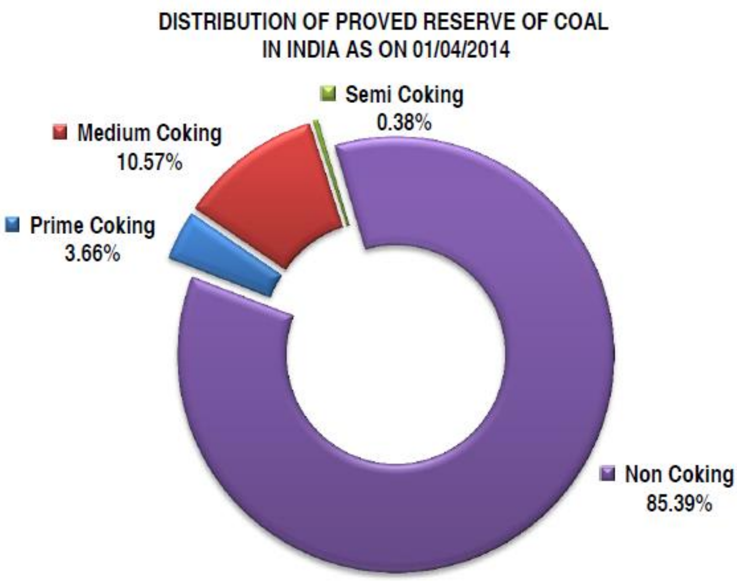
Fig. 1.2: Region-wise coal reserves in India

1.3 Coking Coal and Non-Coking Coal Reserve in India

Table 1.2: Coking coal and non-coking coal reserve in India [5] (In Million Tons)

Type of Coal	Proved	Indicated	Inferred	Total
Total	125910	142507	33150	301565
(A) Coking :-				
-Prime Coking	4615	698	0	5314
-Medium Coking	13304	11868	1880	27048
-Semi-Coking	483	1005	223	1709
Total Coking	18405	13570	2102	34071
(B) Non-Coking	107510	128937	31048	267495

(Source: Geological Survey of India)



(Source: Coal directory of India 2013-14)

Fig.1.3 Grade wise coal reserves in India

1.4 Properties of Coal

(a) Chemical Properties: Coal is made principally out of carbon along with variable amounts of different components, essentially hydrogen, sulfur, oxygen, and nitrogen.

Proximate Analysis: - Proximate analysis of coal is done to determine the amount of moisture content, volatile matter content, ash content, and fixed carbon content. The measures of fixed carbon and volatile matter specifically help to the energy estimation of coal. Fixed carbon is responsible for primary heat generation during combustion. High volatile matter substance helps in easy burning of the coal. The ash content is essential in the configuration of the furnace grate, burning volume of coal, pollution control and ash management system of a furnace.

Moisture: - Moisture in coal must be transported, taken care of and put away. It replaces combustible matter in the coal and diminishes the calorific value of coal. The amount of moisture commonly present in the coal is 0.5 to 10%.

Volatile matter: - Volatile matters refer to methane, hydrocarbons, hydrogen and carbon monoxide, and noncombustible gases like carbon dioxide and nitrogen found. Hence, the volatile matter is an indication of the gaseous fuels presents within the coal. The standard range of volatile matter in the coal is 20 to 35%.

Ash: -Ash content is the amount of impurity present in the coal which is not burnt during combustion.The standard range of ash found in the coal is 5 to 40%.

Fixed carbon: - Fixed carbon is the hard fuel left in the furnace when the volatile matter is driven off. It comprises for the most of carbon additionally contains some hydrogen, oxygen, Sulphur and nitrogen which has not been driven off with the gases. Fixed carbon gives an idea about the calorific value of coal.

Ultimate analysis: - An Ultimate analysis shows the different natural substance constituents, for example, Carbon, Hydrogen, Oxygen, Sulfur, etc. Ultimate analysis gives idea about amount of oxygen needed for the combustion

Reactivity of Coal: -Reactivity refers to the ability of the coal to react with other gases such as oxygen, carbon dioxide, nitrogen, etc. The high reactivity of coal means the amount of formation of carbon monoxide would be high and hence, iron ore can be reduced better.

(b) Energy value / Heating value

The energy value or heating value or calorific value of the coal is the amount of energy released when combusting unit weight of coal. It is the important parameter for the consideration of the coal as superior or inferior coal and hence their suitability in a different sector such as power sector and steel and iron sector.

(c) Physical Properties

Caking Index: - Caking index is a valuable property in iron and steel industry because a high caking index shows that whether the coal can be used to make coke for feeding into the blast furnace or not. A coking coal has high caking index while non-coking coal has less or no caking index.

Bulk Density: Bulk density is defined as the weight per unit volume of solid fuel. It refers to the amount of material to be accommodated in the reactor and after attaining critical moisture content. Bulk density depends upon the particle size, interspecies space, and decreases with increase in moisture content.

True density: - True density is defined as the weight per unit volume of a very finely powdered sample and hence does not include pore spaces and interstitial spaces. True density is necessary to derive mineral content or gas content by estimating porosity.

Apparent Density and Porosity: - Determining the apparent density and porosity is useful in finding the strength of the coal hence used in various metallurgical applications. Porosity refers to the extent to which the fluid can penetrate the sample. Higher the porosity, higher is fluid penetration, and greater is the rate of reaction. The value of apparent porosity also gives the strength of the sample.

Surface Area: - It is characterized by CO_2 gas adsorption near room temperature since it is hard to define the boundary between interior and the exterior surface of coal. Different type of surface area measurement includes particle sizing photo extinction, methylene blue dye adsorption and gas adsorption.

(d) Mechanical Properties

Strength-strength of coal gives an idea about its disintegration tendency. Higher the strength poor are the tendency towards disintegration. Strength is inversely proportional to porosity. Our aim is to minimize the density nature of coal either during handling or operation in the run. The coal char formed during sponge iron making should have sufficient strength. Otherwise, it will break into fines and choke the voids. As the resulting flow of gases would be blocked

(e) Ash Fusion Temperature or AFT

AFT of coal is a crucial factor for selection of coals in steam power generation as well as sponge iron plant. It provides information to the designer and operators when ring formation will likely to take place in the rotary kiln. AFT provides melting and agglomeration characteristics. Ash Fusion Temperature of coal should be sufficiently high to avoid ring formation inside rotary kiln in ironmaking. AFT consists of the determination of four temperatures namely IDT or initial deformation temperature, ST or softening temperature, HT or hemispherical temperature, and FT or flows temperature.

1.5 Selection of Coal for Sponge Ironmaking

The following properties are taken into account while selecting coal for sponge iron making.

i. Chemical properties: - The coal being chosen for sponge ironmaking is considered ideal if the amount of fixed carbon is about forty percent and higher. Fixed carbon content provides some heat energy for the process and also act as a reducing agent. Volatile matter content should be between 25 to 30%. Volatile matter makes combustion of coal easier. However higher volatile matter content would make difficult to control many gases. Ash affects the amount of fixed carbon linearly. As Ash content increases fixed carbon content decreases which in turn increase the amount of residue formation hence energy. Consumption is increased. Therefore, the amount of ash in coal is desired to be at minimum level. Moisture content increases heat loss. Thus, it also has to minimize.

ii. The Very high value for total carbon and hydrogen content is desired in coal because they increase calorific value.

iii. Sulphur Content: - Sulfur affects clinking and enhances slugging tendencies. Thus, it should be very low typically 0.5-0.80%; Phosphorous content should be in the range of 1-1.5%.

iv. Reactivity of coal towards $CO_{2:}$ -This is a major factor for utilization of coal in sponge iron making higher reactivity means a higher reduction of iron ore normal value is more than 2cc/gm/sec.

v. Calorific value: - Higher calorific value would increase the heat generation and hence less volume of coal would be required for the plant.

vi. Ash fusion temperature (AFT): - A higher value of AFT is admired in sponge ironmaking to avoid ring formation in the furnace. The IDT should be greater than working temperature of the furnace by value at least 130-150^{0}C and also soften temperature should exceed 1300^{0}C.

vii. The strength of char: - The coal char prepared from coal must possess higher strength because reduction ability is increased in char having higher strength.

viii. Bulk density: - In Industry bulk density affects shipping cost of the coal and efficiency of the coal. Its value should be more than 300kg/m^3.

ix. The size of coal: - Size of the coal chosen should be optimum in size. If size is more, less would be the surface area and hence its ability to react with gases would decrease, on the other hand if size is very less it results in less porosity and gases cannot escape.

1.6 Selection of Coal for Thermal Power Plants

The coal quality has a major influence on the design of a power plant, as well as its operation and performance. When determining the quality of coal for thermal power plant, several properties are considered. These include Heating value, Volatile Matter , Sulphur , moisture and ash content.

i. Heating value – Heating value or calorific value is the major factor for selecting coal in thermal plants. Caloric value is the amount of heat generated by combusting of per kilogram of coal. In thermal plants quantity of coal for producing power is estimated by knowing the calorific value of the coal.

ii. Fixed carbon content – A higher fixed carbon content results in a high calorific value. Hence, coal with high carbon content is desired in thermal plants.

iii. Volatile matter content – When coal is combusted some gases like H_2 and CH_4 are expelled out. These are expressed as volatile matter in the coal. Higher Volatile matter results in high combustion but reduced calorific value hence the coal being selected for thermal plants should have optimum value.

iv. Sulfur content - The Sulfur substance of coal is an essential thought in coal use since it can add to expanded air contamination. When coal is burnt, the sulfur contained in the coal frames sulfur dioxide, which can add to bringing about acid rain. It can likewise consolidate with ash particulates to bring about pollution. To reduce the impact of sulfur on air quality, coal with low sulfur substance ought to be utilized.

v. Ash - Ash may consolidate with different equipment of the plant which influences the operation of the plant, diminishing its proficiency. The residue substance of coal can extend between 3-50 percent Ash substance of coal ought to be minimized through mixing or washing.

vi. Moisture content - Most coals contain some dampness. A huge extent of this can be expelled by warming the coal at generally low temperatures to dry it out. High dampness substance of coal lessens evaporator effectiveness it additionally adds weight to the coal which builds the expense of transportation. So the coals being supplied to thermal plants should be examined keeping moisture as low as possible.

1.7 Introduction of Coal Char

Coal char is the hard matter left after removal of light gases and tar from solid coals. Char is produced when non-coking coal is carbonized in the absence of oxygen. Coal char has higher strength than coal because C-C bond is strengthening as carbon content is increased while heating. Char is prepared from the coal by the process called carbonization. Carbonization involves heating of coal to high temperature in the absence of oxygen which causes incomplete burning of coal.

$$\text{Non-coking coal} \xrightarrow{\text{carbonization}} \text{char + coal gases}$$

1.8 Year Wise Production and Export-Import of Non-Coking Coal in India

Table 1.3: year wise production and export-import of coal in India in previous ten years [6]

(In million tons)

Year	Production	Export	Import
2004-05	352.528	1.134	12.025
2005-06	375.528	1.943	21.695
2006-07	398.735	1.447	25.204
2007-08	422.627	1.591	27.765
2008-09	457.948	1.546	37.923
2009-10	487.629	2.180	48.565
2010-11	483.147	1.764	49.434
2011-12	488.290	1.917	71.052
2012-13	504.820	2.387	110.228
2013-14	508.947	2.144	131.248

(Source: Coal directory of India 2013-14)

1.9 Difference between Coking Coal and Non-Coking Coal

- Coking coal particles stick to each whereas this is not so in the case of non-coking coal.
- Coking coal particles exhibit Fluidity at a temperature range of 350-500^0 C. It means they behave like a viscous fluid. Whereas non-coking coal does not exhibit plasticity, hence they are not like a viscous liquid.
- The plasticity of coking coal is due to the presence of a significant amount of vitrine content whereas in non-coking coal vitrine content is very less.
- Coking coal reserves are very limited in nature in India. The total coking coal reserve is around 30 billion tons, only 15% of total coal reserve. Whereas non-coking coal

reserves are plenty in nature In India, the total non-coking coal reserve is 180 billion ton, i.e,85% of total coal reserves.

- Coking coals are mostly exploited for use in the iron making in iron blast furnace whereas non-coking coals are used in making sponge iron, thermal power plant, brick kilns, cement industries, railways, etc.
- Only bituminous coal is caking in nature whereas rest other is non-coking.
- Coking coal is costly material whereas non-coking coal is relatively cheaper.
- Coking coals, in general, have a higher caking index (>15).All coking coals are coking in nature whereas non-coking coal has nil or much lower caking index. Very lesser number of non-coking coals is caking in nature
- Carbonization of coking coal produces coke and coke oven gas.

$$\text{Coking coal} \xrightarrow{\text{carbonization}} \text{coke + coke oven gases}$$

Whereas carbonization of non-coking coal gives coal char and coal gas.

$$\text{Non-coking coal} \xrightarrow{\text{carbonization}} \text{char + coal gases}$$

- Fixed Carbon content and energy value of coking coal are relatively higher whereas fixed carbon content, and energy values of non-coking coal are in general lower than those of coking coal.

1.10. Comparison between Coal Char, Charcoal, and Coke.

Parameter	Coal char	coke	Charcoal
1.preparation	Coal char is obtained from carbonization of non-coking coal.	coke is produced by carbonization of coking coal at a temperature of 1250^0C	charcoal is obtained from carbonization of wood in the temperature range 400-1000°C
2.calorifuc value	Energy value of coal char is lower.	Higher energy value than coal char.	It has highest calorific value.
3.fixed carbon content	Fixed carbon content is lowest in coal char.	Higher than coal char.	Fixed carbon in charcoal is the highest.
4.Volatile content	Highest volatile matter content in the	Lowest volatile matter content	Volatile matter in charcoal is greater than

	coal char.	present in the coke.	coke but lower than coal char.
5.Ash content	High ash content (20-50%)	Intermediate ash content (20-30%)	Lowest ash content (2-8%)
6.Reactivity	Reactivity towards carbon dioxide is greater than coke but lower than charcoal	It has the lowest reactivity towards carbon dioxide.	Reactivity towards carbon dioxide is highest.
7.Density	Low	Higher	lowest
8.Porosity	Lowest	Higher porosity (38-45%)	Highest porosity (more than 50%)
9.Structure	Amorphous	Semi-crystalline	Highly amorphous
10.Bond Strength	C-C bond strength is lower than coke but higher than charcoal.	Highest bond strength	Lowest bond strength.
11.Mechanical strength	Intermediate	Higher	Lower
12.Reduction potential	Intermediate	Higher	Lower
13.Sulphur content	Sulphur content is high (0.5-2%)	Lower Sulphur and phosphorus content (0.5-0.7%)	It has negligible Sulfur and phosphorus content.
14. Thermal conductivity	Intermediate	Higher	Lower
15.Abrasion resistance	Poor	Good	Very poor
16.Adsorptivity	Low	Lower	Higher
17.Application	Coal char is used in sponge iron making, power plants and cement industries.	Coke is used in a blast furnace in primary steel making process.	charcoal used in the manufacture of Indian ink, extraction of gold and silver, and in medicine.

1.11 Objectives

The objectives of the present project work are as follows:-

(i) To carry out proximate and ultimate analysis of coals collected from various parts of the country.

(ii) To produce char from selected coal samples.

(iii) To carry out proximate analysis of the Chars produced.

(iv) To determine the calorific values of all the coal samples and their chars.

(v) To determine the reactivity of chars with the carbon dioxide.

(vi) To determine of porosity and density of the coal samples and their chars.

(vii) To determine of Ash fusion temperature (IDT, ST, HT, FT) of the coal ashes.

(viii) To investigate the variation in the properties of coal and chars with the carbonization temperature.

(ix) To investigate, results so found to select the superior quality of coal employed in sponge Ironmaking.

CHAPTER 2

LITERATURE REVIEW

Kumar and Patel: Characteristics of non coking Coals (2008) [7]

Both have worked on the characterization of non coking coal for its physical and chemical properties. They obtained coal samples from various coal fields reserve in Orissa. They found that most of the coals had no caking properties. They also found that Ash fusion Temperatures for these coals are very high (IDT>1100, ST>1349, HT>1500 ,FT>1500) Sulfur content for these coals were found to be in the range of 0.4 to 0.6 which is not so problematic. The result shows that in coal chars as the fixed carbon content increases, reactivity of coal towards carbon dioxide (CO_2) decreases. Most of the chars showed high reactivity (more than 4cc/gm/^{0}C) some investigation were also performed on the reduction strength of coal samples and found that reactivity of char and time of reduction led to high reduction of iron ore. They recommended utilization of these coals in sponge iron plant after blending and beneficiation.

D.D Haldar:[8]

He has worked upon beneficiation of non-coking coal. Beneficiation process improves the property like calorific value, char characteristics and its strength, volatile matter content. These properties are most useful for production of Iron. The study shows coking coal required good coking property while for non-coking coal the desirable aspect is combustible behavior.

Byong Chul Kim:[9]

Prof. Byong Chul Kim studied the variation in properties of coal due to carbonization temperature on. He discovered when temperature increased, reactivity decreased. He found carbonization temperature also affect gasification of coal because at higher temperature number of active carbon side is reduced which eventually reduce the gasification rate. The result is more profound in low grade coal as compared to high grade coal. Coal samples having higher volatile matter is greatly affected by carbonization temperature. Heating rate during carbonization also affects product yield and distribution. If heating rate is very high it will enhance char reactivity and decrease its gasification rate.

Prof. Sen K emeritus (2008) [10]

He studied the physical and chemical properties by proximate analysis of coal and other properties (ash fusion temperature, , hydrogen, chlorine and sulfur content) also and energy value of coal samples were also studied by him obtained from different parts of country. He found energy value in the extent of 4900-6200 Kcal/

kg most of the sample had high Ash fusion temperatures (IDT>1280). These coals had high fixed carbon content. All these results are useful in Sponge ironmaking

Kumar M. and Patel [11]

They have studied the reduction of iron ore obtained from different mines of Orissa with noncoking coal. They discovered that all the coal samples had high reduction ability at the beginning, however, it reduced after some time (30 minutes) Result indicates slow heating rate yield to high reduction potential.

Kumar and Gupta : Carbonization analysis [12]

Their investigation on carbonization of Non-coking coal obtained from coal mines in Dhanbad show the effect of carbonization temperature on coal char properties. Increases in temperature from 400C to 1000^0C increase the removal of gas from coals sample resulting in lower volatile matter content and Hydrogen content which eventually decrease the energy or calorific value. They investigated the reactivity of char at unlike carbonization temperatures (400^0C,600^0C, 800^0C, 1000^0C) and found an increase of carbonization temperature decrease the char reactivity with carbon dioxide . Apparent density decrease initially with rise in carbonization temperature till 400^0C and then after increase while the true density increase continuously.

Kumar and Gupta (1994) [13]

They worked on wood char properties and relationship with reactivity. They found reactivity decreases with increases in carbonization temperature and soaking time. They also found that rapid heating (30C/min) increases the reactivity significantly than the slow heating rate (4c/min).

Arpita Sharma et.al (2014) [14]

They studied properties (physical and chemical) of the coals procured from Meghalaya. They also studied main oxides and minerals present in the ash of these coal samples. They investigated the effect of oxide towards Ash fusion temperature. They found that value of IDT decreases with increases in SiO_2 concentration. Also, the value of IDT increases slightly with an increase in Al_2O_3 concentration. Some oxides like CaO, MgO and Fe_2O_3 also found acid oxides are a major disturbing factor for slag formation compared to basic oxides.

Kamishita M et.al (2008) [15]

They have investigated porosity and reactivity of the lignite char due to carbon accumulation and found a technique to enhance the reactivity of coal char keeping deposition of carbon as low as possible. They showed decomposition of carbon from temperature range 815^0C to 850^0C due to decomposition of CH_4. The size of the pore for carbon deposition is much more. Acid washing technique can be used to remove the inorganic impurity hence reduce the porosity.

Kirov and Peck (1970) [16]

They studied the physical and chemical properties of coal char obtained at a temperature of 425-800^0C by the process of carbonization they used batch fluid bed technique for describing carbonization temperature and establish a connection among the volatile matter content, carbon and hydrogen content of the char. They found the rise in carbonization temperature resulting in decreases in volatile matter content, increases in hydrogen content due to increase in carbonization temperature.

Marcilla A et. al (1996) [17]

They investigated effect rate of heating on characteristics of sub-bituminous coal. They investigated gradual rate of heating (5K/min) and rapid heating (100K/Sec). They combined slow heating and fast heating for analyzing different carbonization process. They sound that reactivity of char those produced from gradual rate of heating, is lower. Chars produced at fast rate shows higher reactivity.

Binayak Mohapatra and Dharanidhar Patra [17]

They investigated characteristics of iron ore reduction by the Non-coking coal in the temperature of range 850-1000^0C. They observed the time of reduction and temperature affects the amount of reduction. They found during reduction time of 15-120 minutes amount of reduction is not affected by the type of coal.

RJ , S Dutta , Belt and CY, (1977) [18]

They worked on char gasification in presence of carbon dioxide performed between 340-1100^0C. They studied this into two stage first one was the pyrolysis of coal and second was the reaction between char and CO. They found that volatile matter content affects the Pyrolysis of the char or coal and heating rate. The reactivity of char with CO depends on coal seam from where char is derived. Reactivity of both (char and coal) are affected by its porosities and these are function of temperature. The reactivity rate of char with carbon dioxide have less effect due to nitrogen present in the surface area of pores and has a little tendency towards reaction.

N Narcin , S Aydin, K Sesen, F Dikec. [19]

They found ability of coal to reduce iron ore is dependent on amount of carbon content (fixed and total) which was obtained by Proximate analysis and Ultimate analysis. They performed iron ore reduction with soft coal(lignite) in a rotary kiln and established that coal utilization ratio (C_{fix}/C_{ut}) 0.40 and temperature 1000^0C took 90 minutes to complete the reduction of iron ore. This result may be a handful in industrial application.

M. Hememmati, J. Vahdati Khaki, A. Zabett et.al [20]

They investigated the reduction of iron fine by non-coking coal and also studied devolatilization of noncoking coal in the isothermally Argon atmosphere. It was found maximum weight loss and devolatilization occurs at temperatures range 640^0C-725^0C. Influence of size of the coal particle of and rate of heating were analyzed . It was found that increase in rate of heating and size of particle decrease the devolatilization. They obtained 40 percent of reduction on increasing the temperature to 950^0C.

Sinha K.M.K, Sharma T., Haldar D.D. [21]

They investigated the Iron ore reduction with Non-coking coal employed for DRI production. They studied the consequence of different factors such as Time ,Temperature, and Fe_2O_3:C ratio. They found maximum reduction obtained at Fe_2O_3C ratio of 1:1.75, at the temperature 1323 keeping after 90 minutes of reduction time. The highest amount of reduction obtained at this condition was 89.1 percent.

Akanksha Mishra, Shalini Gautam, Tripura Sharma [22]

Akanksha Mishra et. al compiled the investigation performed by many scholars on the effect of char structure on coal gasification. They summarized that the structure of char is major factor to estimate properies of coal gasification. Parameters responsible for controlling the properies of char gasification include micropore, and pore during pyrolysis, and char surface area

Sang Kyum Jim et. al [23]

They worked on the kinetic characterization of chines. Low-rank lignite coal and CO_2 gasification of these chars performed by isothermal gravimetric at temperature 1073 K and CO_2 concentration 10-90% gasification rate was found to rising and attains maximum when amount of carbon dioxide obtained was 70% CO_2 and then decreases. The rate of the char gasification with carbon dioxide is rapid and followed by Na_2CO_3>K_2CO_3>dolomite.

S.Biswas, N. Choudhary, P.Sarkar et. al [24]

They studied burning characteristics of a couple of Indian Coals having same grade but different mineral matter content using TGA and DTF. They found that burning with thermos gravimetric analysis profile indicated additive as well a non-additive effect while DTF behavior was non-additive. Results indicate coal blend with high ash content less than fifty percent proves improved combustion than the single coal.

Vivek Kumar and V.K. Saxena [25]

They worked on effect of coal beneficiation on properties of low volatile coking coal coal . They showed LVCC constitute 50% of coking coal in India having high amount of ash and Cleaning potential. The high content of ash is lowered by process called washability which gives result that breaking of coal into crushes with size ½ inch or less is economical. Results conclude that import of coking coal can be minimized by proper utilization of low volatile coking coal coals after proper beneficiation .

CHAPTER 3

EXPERIMENTAL

3.1 Selection of Materials

Coal samples for this project were obtained from different coal fields of Chattisgarh, Orissa, and West Bengal. These coalfields are SECL Korba, Jindal, Gopalpur, Basundhara, Lingaraj and Asansol coalmines.

(a) **(b)**

Fig 3.1: Coal sample (a) Lumpy coal (b) Powdered coal

3.2. Preparation of Coal Char and Determination of Char Yield

Coal char for the reactivity and other physical and chemical characterization was prepared by the process called carbonization. In this process weighted amount of air-dried coal samples were taken in a steel container with top covered ensuring a small opening for emission of gases. Steel container was then kept inside the furnace and allowed to heat gradually from normal temperature to predefined carbonization temperature of 400, 600, 800^0C and 950^0 C with soaking time 1 hour followed by furnace cooling. Weight of resulting char was measured to calculate amount of char produced and char was then processed for proximate analysis and other studies.

$$\% \text{ Char yield} = \frac{Weight\ of\ char\ produced}{weight\ of\ coal} \times 100$$

3.3. Proximate Analysis of Coal and Chars

Proximate analysis provides knowledge of moisture content, volatile matter content, Ash content and fixed carbon content in the coal and char. It was determined as per Indian standard [26]. The processes are described as follows.

3.3.1 Determination of Moisture Content

Coal and char powder of size -72 mesh size or -212 microns was prepared and 1 gm of the dried sample were taken in a crucible and kept inside an oven for one hour at a temperature 105-110^{0}C. The sample was removed from the furnace and weight was measured again. The loss in weight was measured as moisture content.

% moisture = % Loss in weight of the sample

3.3.2 Determination of Volatile Matter Content

Dried sample of coal and char of -72 mesh size or -212 microns weighted 1 gm was taken in the crucible of silica enclosed with cap and placed inside the furnace at a temperature of 925^{0}C and held for 7 minutes at this temperature after that crucible was removed from the furnace and weight was again measured. The amount of Volatile matter present was calculated as follows

% volatile matter = (%weight loss — % moisture content)

3.3.3 Determination of Ash Content

1gm of dried sample of coal and char of – 72 mesh size or -212 microns was taken in a narrow disc like the crucible of silica and then placed inside a furnace at a temperature 775^{0}C-800°C and kept inside the furnace for one hour until complete burning took place. It required occasional stirring for uniform burning after that sample was removed from the furnace and weight was measured. The residue amount left was the ash present in the sample

% Ash content = % weight left in the sample after combustion

3.3.4 Determination of Fixed Carbon Content

After calculating moisture content, volatile matter content and Ash contend, fixed carbon content can be determined as follows

Fixed carbon % = 100- (% moisture + % ash + % volatile matter)

3.4 Ultimate Analysis of Coal

Ultimate analysis of coal provides information regarding total carbon content ad hydrogen content. Ultimate analysis of some of the coal samples has been performed in Punjab University, Chandigarh through the personal contact.

3.5 Determination of Calorific Value of Coal and Char

Calorific value can be defined as the amount of energy released by combustion of unit weight of the sample (coal/ char). The instrument used for this experiment was oxygen bomb calorimeter as shown in fig. 3.1(b) [27].

Process: 1 gm of coal sample or char sample was converted into the form of a briquette fig3.1 (a) and then placed inside the oven for drying purpose. Now the sample was taken out and charged into a bomb and cotton thread was made to touch the sample. After that oxygen gas was allowed to pass with a pressure of 25-30 atm. Now the bomb was placed in the water-filled vessel. The whole set of the instrument was then connected with a power source for ignition. The briquetted coal or char was combusted in the atmosphere of oxygen.

Fig. 3.2 (a): Briquetted Coal sample

Fig. 3.2 (b): Oxygen Bomb Calorimeter

As soon as a rise in temperature observed, its value was recorded and after every minute, temperature value was recorded until it reached its maximum value, after combustion cooling took place in the presence of water.

Gross calorific value calculated as

$$\text{GCV} = \left[\frac{\{WE \times (\Delta T + .04)\}}{W}\right] - heat\ realesed\ by\ burning\ of\ fuse\ wire\ and\ cotton\ thread$$

WE = water equivalent took as 1987 Kcal/ ^{0}C

ΔT = difference in maximum and minimum temperature.

W = weight of the briquetted coal

3.6 Determination of Apparent Density and Apparent Porosity of Coal and Chars

Apparent density and apparent porosity of coal and chars were calculated by hot boiling water test. A coal or char sample of 15-20mm size was placed inside an oven at a temperature of 100^0C for drying purpose. The sample was then taken out and weight was measured. The thereafter dried sample was suspended in a hot boiling water beaker and kept for about 20 minutes. The weight of sample with the thread was measured in a chemical balance. Now, Suspended weight was kept aside and weight of thread dipped in water was measured.

At the end, the weight of water- soaked sample was measured [28].

Apparent Density = $D/\{D-(S-s)\}$

Apparent porosity = $\dfrac{(W-D)}{\{D-(S-s)\}}$

Where,

D = weight of dried coal or char sample

W= weight of water-soaked sample in air

S= weight of suspended sample and thread when dipped in water.

s= weight of suspended thread only when dipped in water.

3.7 Determination of Ash Fusion Temperature of Some of the Coal Ashes (AFT)

One important property which should be determined while using coal in sponge iron plant is Ash Fusion Temperature. AFT gives an idea of melting characteristics of coal ash.

Process:- AFT is determined as per German standard [29]. The sample was prepared by taking 3 to 4 milligram of coal ash and then kept in a special type of furnace equipped with a microscope. The upper-temperature limit was 1600^0C the heating rate was set at 10^0C/m. Initially, the shape of the sample was cubical as the temperature started increasing a point comes where shrinkage in shape was observed. This temperature was recorded and expressed as IDT or initial deformation temperature. The sample was sustained to heat further. After some time rounding of corner took place at a certain temperature which was recorded as softening temperature (ST) upon the further heating shape of a cube of the sample was distorted to such extent that it appeared as a hemisphere. This particular temperature was recorded as hemisphere temperature (HT). Finally, as heating was continued hemisphere sample started melting and flowing. This temperature is called Flow temperature or FT.

Fig.3.3 (a): Leitz heating microscope furnace

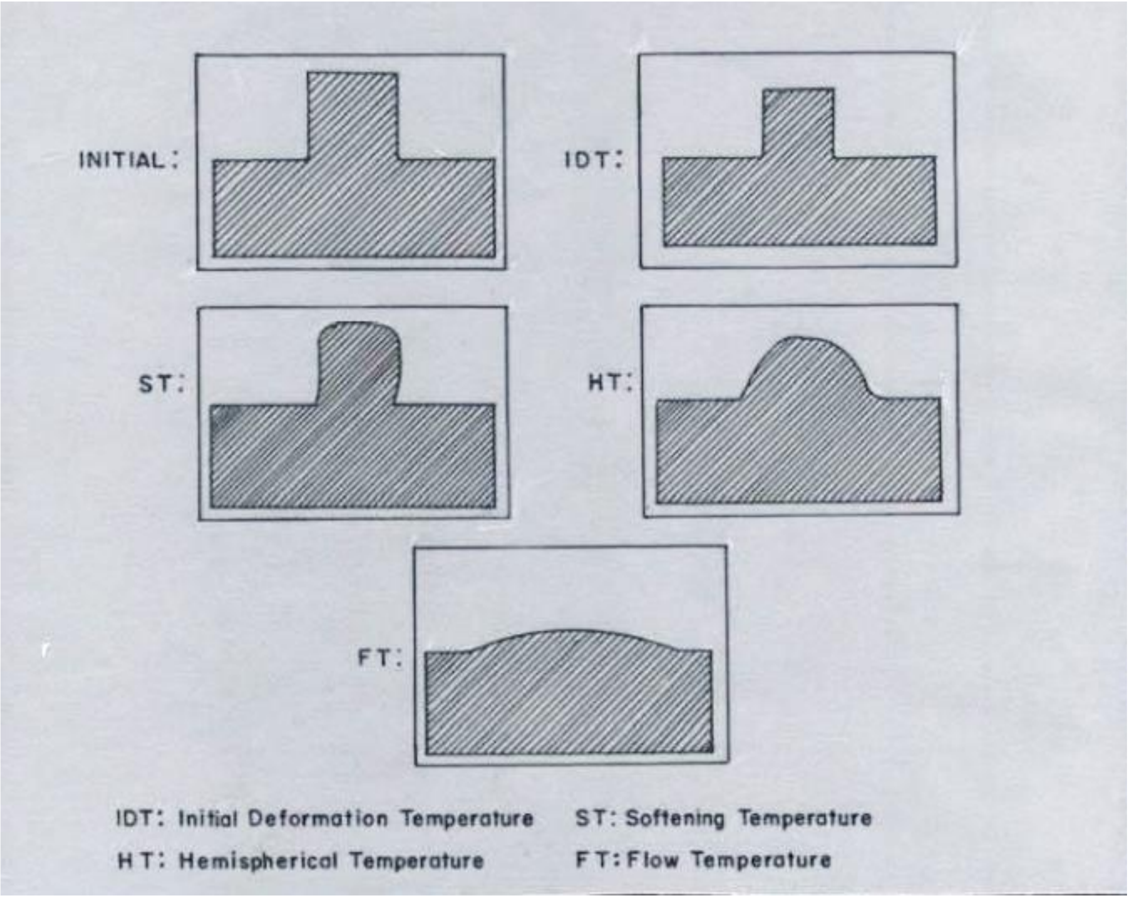


Fig 3.4: Different shapes of the coal ashes during Ash fusion temperature

3.8 Determination of Caking Index of Coal

The caking index was determined as per Indian standard [30]. Coal sample of -72 mesh size in the form of powder blended with sand of the identical size in a dissimilar ratio so that total weight of coal sample and sand came out to be 25g. The mixture of sand and coal was then taken in a crucible and kept inside furnace maintaining a temperature of 925^0C for 7 minutes only. The crucible was then taken out and allowed to cool in air. The crucible was inverted after cooling and a cake of mixture of coal and sand was produced. This cake was subjected to stress under the weight of 500gm. The force applied by the weight caused the cake to deform and some powder was produced. The weight of the powder precipitated from each cake was measured. The cakes from which weight of the precipitated powder was less than 1.25gm, those cakes were considered for the caking index.

3.9 Determination of Reactivity of coal chars

Reactivity of the coal char is the ability to react with carbon dioxide. It was determined as per Indian standard [31]. Coal was carbonized to form coal char by combusting coal in the absence of air maintained at a temperature of 950^0C for a couple of hours. Char thus produced was processed for proximate analysis with 5gm was taken in tubular furnace fastening the end of the sample. The sample was placed in the constant heating area, After some time Nitrogen gas was allowed to pass at the rate of 50cc/min till the temperature reached 1000^0C. When the temperature attained 1000^0C, nitrogen gas was stopped to supply and carbon dioxide started to . When the temperature became stable, carbon dioxide gas supply was stopped and supply of nitrogen started again at a rate of 50 CC/minute till the temperature of the sample reached to 150^0C. The reacted sample was removed from the furnace and weight was measured.

$$\text{Reactivity} = \frac{11.61*W}{\left(5*C_{fix}-\frac{W}{2}\right)}$$

W = Weight loss, C_{fix} = Fixed carbon content of the char.

(a)

(b)

Fig 3.5: Reactivity of coal chars (a) Tubular furnace (b) Cylinders of nitrogen and carbon dioxide

CHAPTER 4

RESULTS AND DISCUSSION

The results of the experiments carried out for the present work are listed in from Tables 4.1 to 4.7 and have been presented in the graphs in Figures 4.1 to 4.12

4.1 Analysis of Chemical Properties of Coals

Table 4.1: Proximate analysis and Ultimate analysis results of the selected non-coking coals

Name of coal mines from where coal samples were collected	Proximate Analysis (wt%)				Ultimate analysis (wt%)	
	Moisture content	Volatile matter content	Ash content	Fixed carbon content	Total carbon content	Hydrogen content
Jindal	2	28	23	47	-	-
Korba	4	25	36	39	56.4	3.45
Gopalpur	1	30	27	42	-	-
Asansol	2	28	13	52	58.6	3.60
Basundhara	7	26	10	57	64.5	4.75
Lingaraj	11	32	17	40	-	-

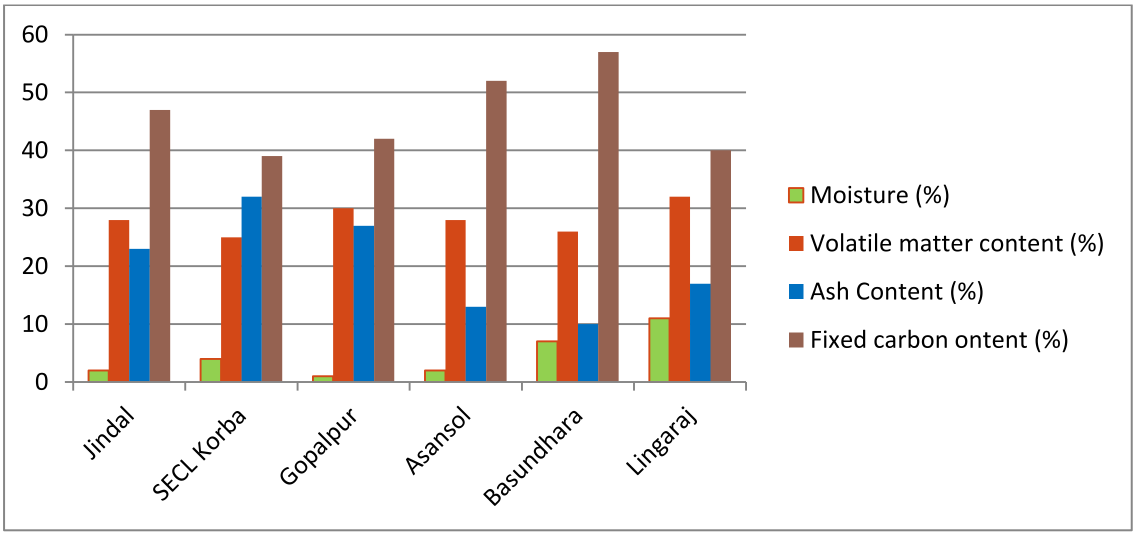


Figure4.1: Results of Proximate analysis of the all the coals samples in chart

Results obtained from Proximate analysis of all the coals have been listed in table and depicted by the chart. From the table and chart, we can clearly say that coal sample from Basundhara mines is having the highest amount of fixed carbon content followed by Asansol, Jindal, Gopalpur, Ligaraj and Korba mines respectively. We also found that Korba,SECL coal sample has highest ash content while the volatile matter is highest in Lingaraj mines.

4.2 Calorific or Energy Value of the Coal

Table 4.2: Energy value of all the selected non-coking coals

coal sample	Gross calorific value (kcal/kg)
Jindal coal field	6383.22
Korba,SECL	5815.20
Gopalpur,MCL	6117.420
Asansol	7428.28
Basundhara	8110.56
Lingaraj	5920.36

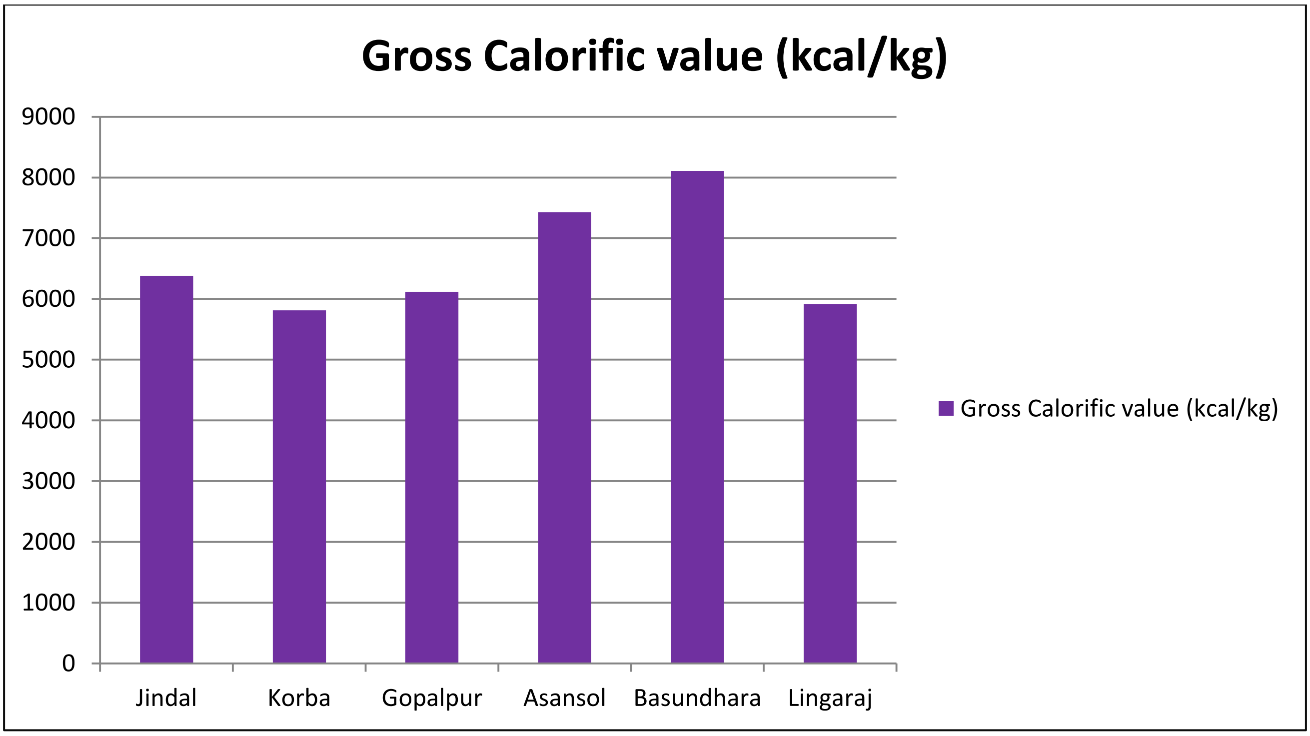


Fig 4.2: GCV of all the coals in form of chart

Energy values or Calorific values of all the coals have been tabulated (Table 4.2) and plotted in the bar graph (Fig 4.2). Results indicate that Basundhara coal has highest energy value followed by Asansol, Jindal, Gopalpur, Lingaraj and Korba respectively. The high energy value of coal is due to the high amount of carbon present.

4.3, Physical Properties of Coal

Table 4.3: Apparent porosity and density and caking index of all the coal samples

Coal sample	Apparent porosity (%)	Apparent density (g/cc)	Caking index
Jindal coal field	26	1.5	Nil
Korba,SECL	16	1.6	Nil
Gopalpur,MCL	37	1.3	Nil
Asansol	28	1.4	2
Basundhara	32	1.5	2
Lingaraj	17	1.6	Nil

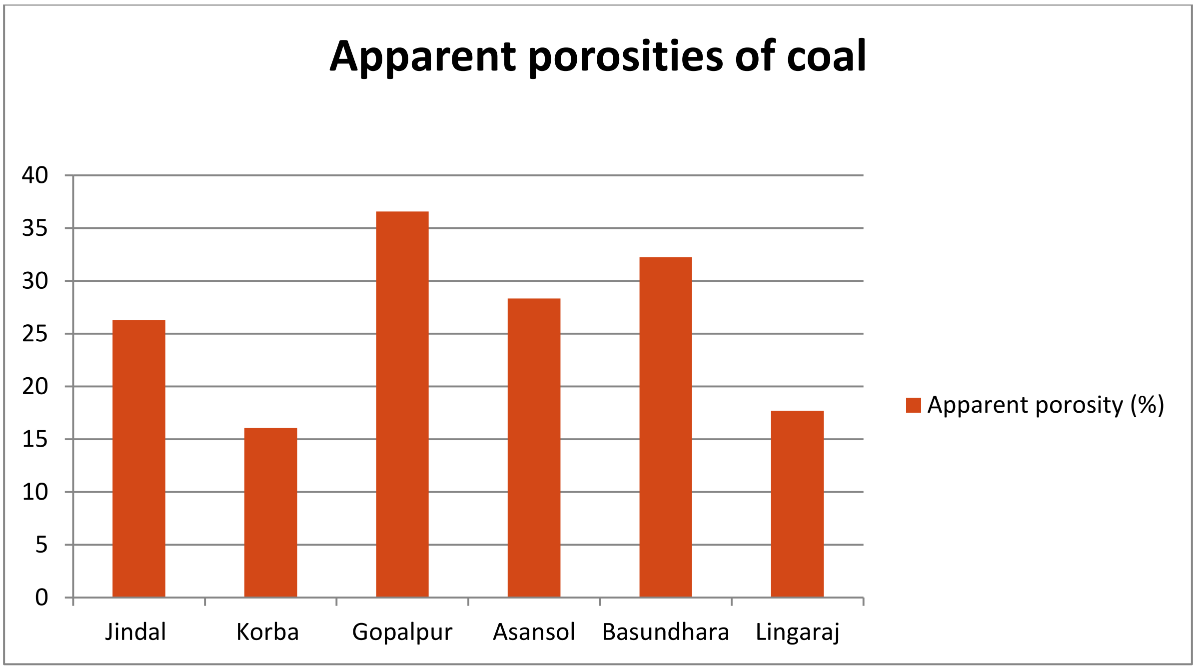


Fig 4.3: Apparent porosity of all coal samples in chart

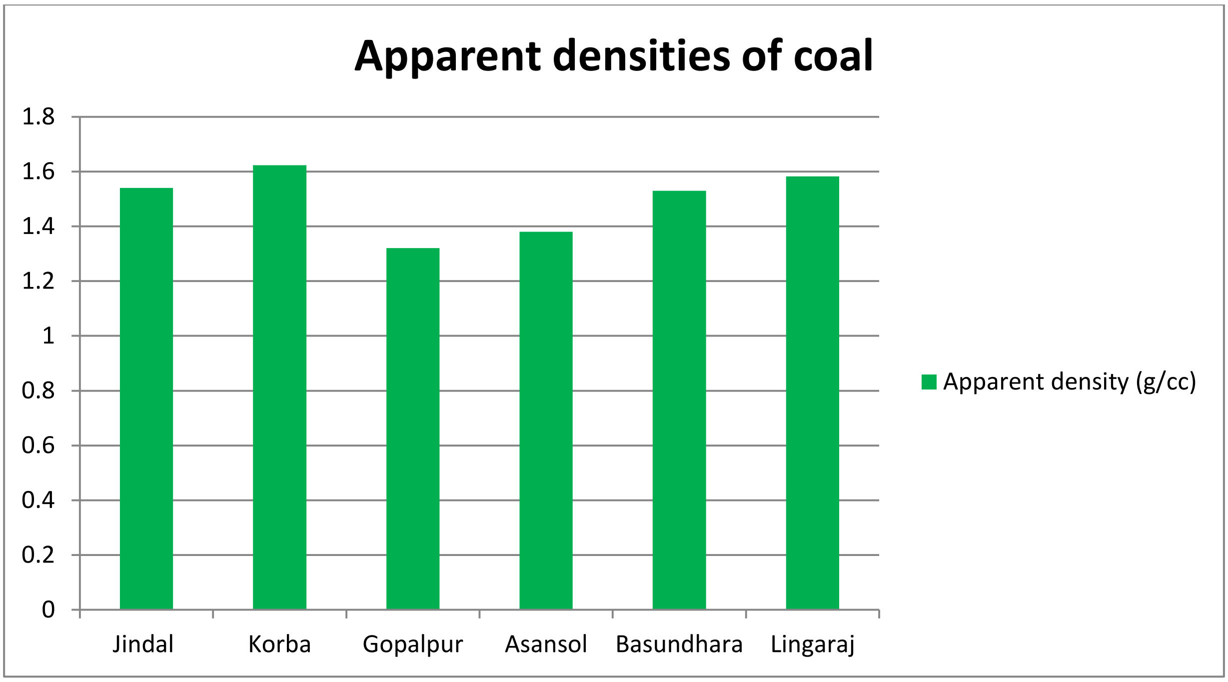


Fig.4.4: Apparent density of all the selected coal samples in chart

Physical properties of coal like apparent porosity, apparent density, and caking index have been examined and results are shown in Table 4.3 and plotted in the Graph 4.3 and 4.4 The values of apparent porosities of all the coals were found between 16.04 – 36.56%. Porosity makes the coal more reactive.

The caking index indicates affinity to fuse coal particles together. Non-coking coal exhibits a lower value of the caking index i.e. less than the 3.Caking index of the selected coal samples (Table 4.3) has been determined and results are expressed in the table above. From the value, we found that most of the coal samples have nil caking indexes. However, some coal samples show caking index greater than zero as in Basundhara, Asansol, and Jindal coal. Caking index values of these three coals were found as 2.

4.4 Proximate Analysis Results of Coal Chars

Table 4.4: Effect of carbonization temperature on the properties of coals chars

Coal Mines	Carbonization temperature (°C)	Proximate analysis (wt%)				Reactivity of char at 950°C(cc/gm/sec)
		Moisture content	Volatile matter	Ash content	Fixed carbon content	
Jindal coal mines	400	2	21	28	49	-
	600	1	12	32	55	-
	800	1	7	35	57	-
	950	nil	3	37	61	3.73
SECL, Korba	400	3	18	39	40	-
	600	2	11	42	45	-
	800	1	5	45	49	-
	950	1	1	47	51	3.46
Gopalpur,MCL	400	1	22	32	45	-
	600	1	15	35	49	-
	800	nil	6	41	53	-
	950	nil	2	43	55	-
Asansole	400	2	23	19	56	-
	600	1	12	27	60	-
	800	1	5	30	63	-
	950	nil	2	32	66	5.14
Basundhara	400	5	21	16	58	-
	600	3	16	19	62	-
	800	2	7	26	65	-
	950	1	2	29	68	4.95
Lingaraj	400	9	27	22	42	-
	600	7	21	27	47	-
	800	6	12	32	50	-
	950	4	5	38	55	2.89

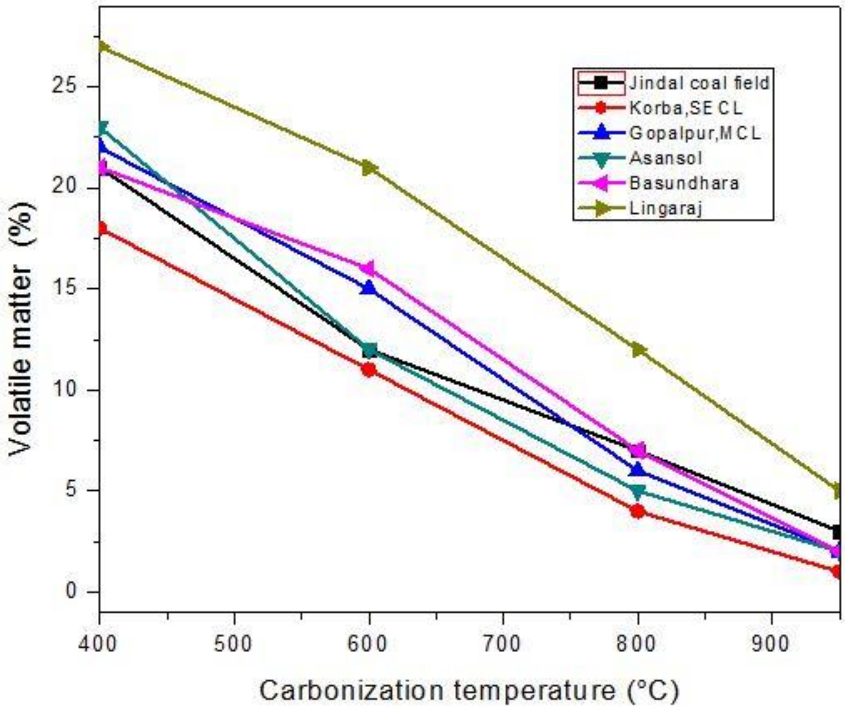


Figure 4.5; variation in volatile matter with rise in carbonization temperature

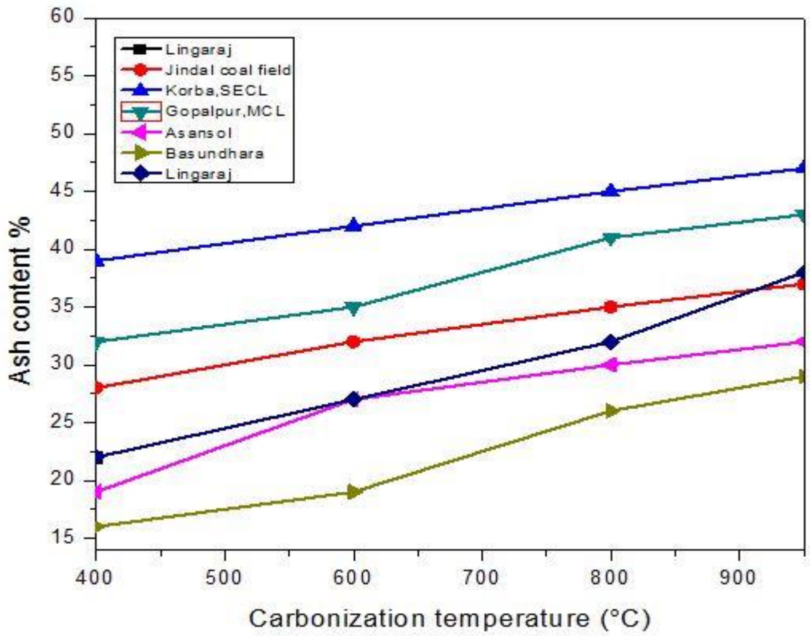


Figure 4.6 , variation in ash content with rise in carbonization temperature

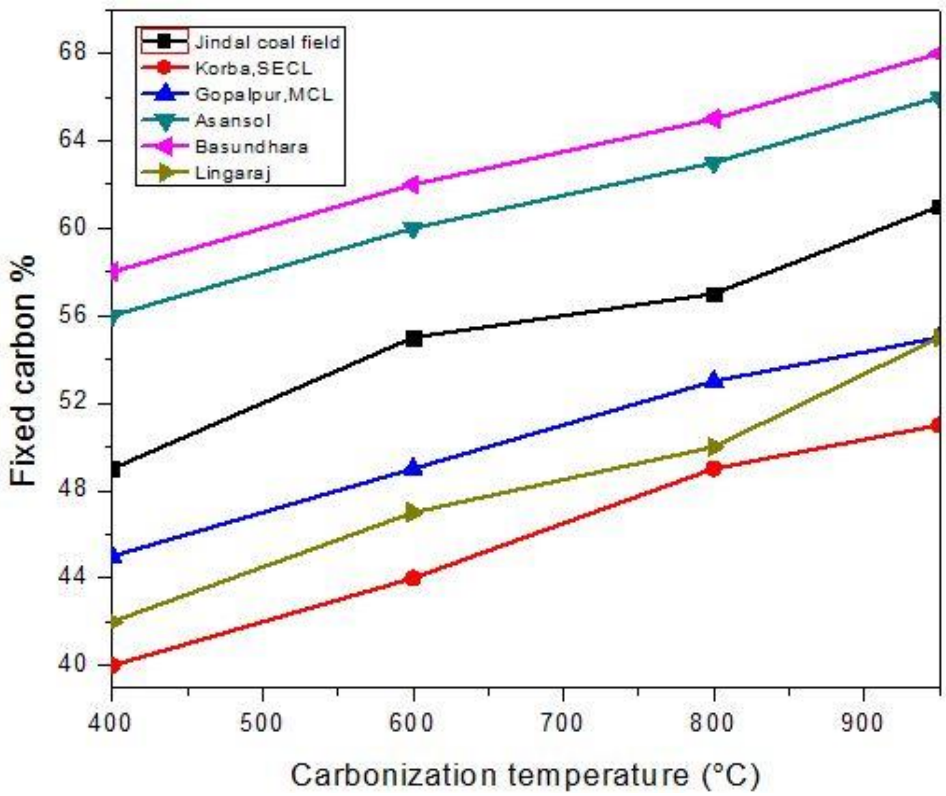


Fig.4.7: variation in fixed carbon content with rise in carbonization temperature

Results of Proximate analysis of coal chars have been enumerated in table 4.4 and variation in ash content,volatile content and fixed carbon content with rise in carbonization temperature have been outlined in the fig 4.5-4.7

As the volatile matter breaks down and driven out from the coal during carbonization, the fixed carbon content will increase by increasing carbonization temperature as shown in fig 4.5; Also, when carbonization temperature increases, moistures are evaporated and other volatile gases also expelled out. Therefore with increase in carbonization temperature, amount of moisture and volatile matter are reduced. On the other hand, heating up of the coal results in more combustion hence more ash will be produced which results in higher amount of ash produced as shown in fig 4.6

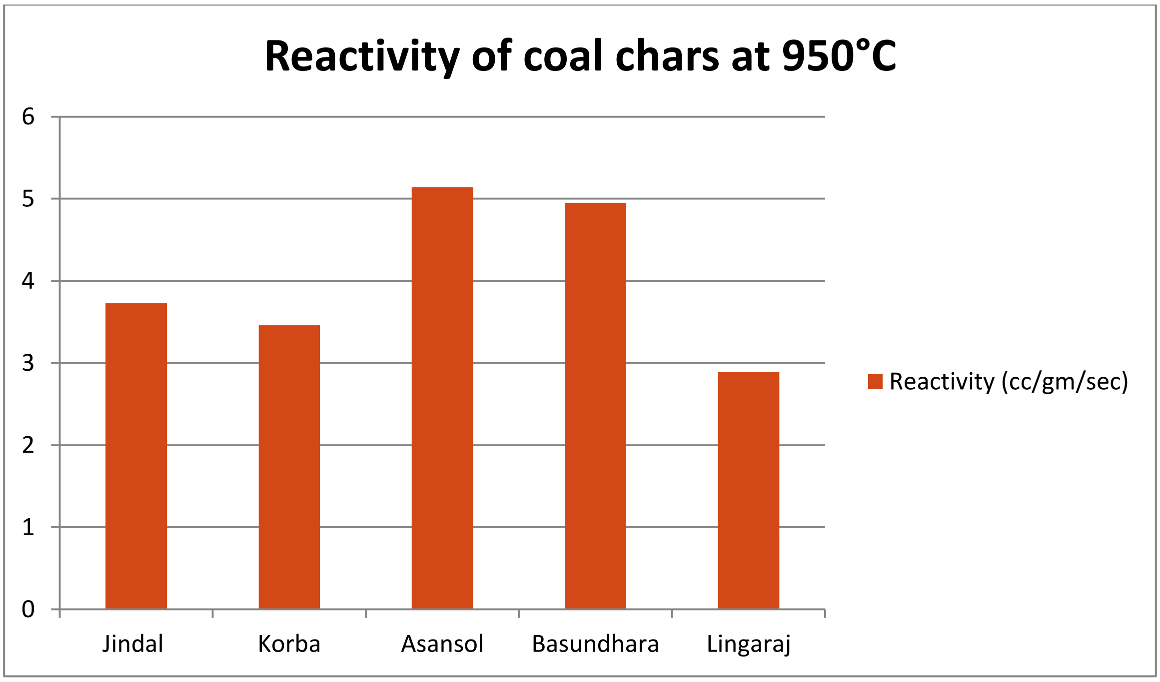


Fig. 4.8: Reactivity of coal chars at 950°C in chart

In sponge Ironmaking char is used to reduce iron ore, if reactivity is good enough (greater than 2cc/gm/sec) iron ore can be reduced more easily.

C + O2 = 2CO (Endothermic reaction)

Additionally, high reactivity permits flexibility in the working parameters of the furnace . For example working temperature of the kiln can be dropped substantially. This will save lots of energy hence productivity of the plant enhanced. High reactivity also reduces the affinity of coal ashes towards agglomeration4.5 Energy Values of Coal Char Produced at different temperatures

4.5 Energy Values of Coal Char Produced at different temperatures

Table 4.5: Variation in GCV of coal char due to rise in carbonization temperature

Coal samples from where char produced	Carbonization temperature (°C)	Soaking time	Gross calorific value (kcal/kg)
Jindal coal field	400	1hr	6488
	600		6488
	800		6562
	950		6712
Korba,SECL	400	1hr	5910
	600		6117
	800		6888
	950		6945
Gopalpur,MCL	400	1hr	6177
	600		6180
	800		6298
	950		6366
Asansol	400	1hr	7547
	600		7628
	800		7710
	950		7785
Basundhara	400	1hr	8176
	600		8252
	800		8320
	950		8397
Lingaraj	400	1hr	6217
	600		6298
	800		6357
	950		6427

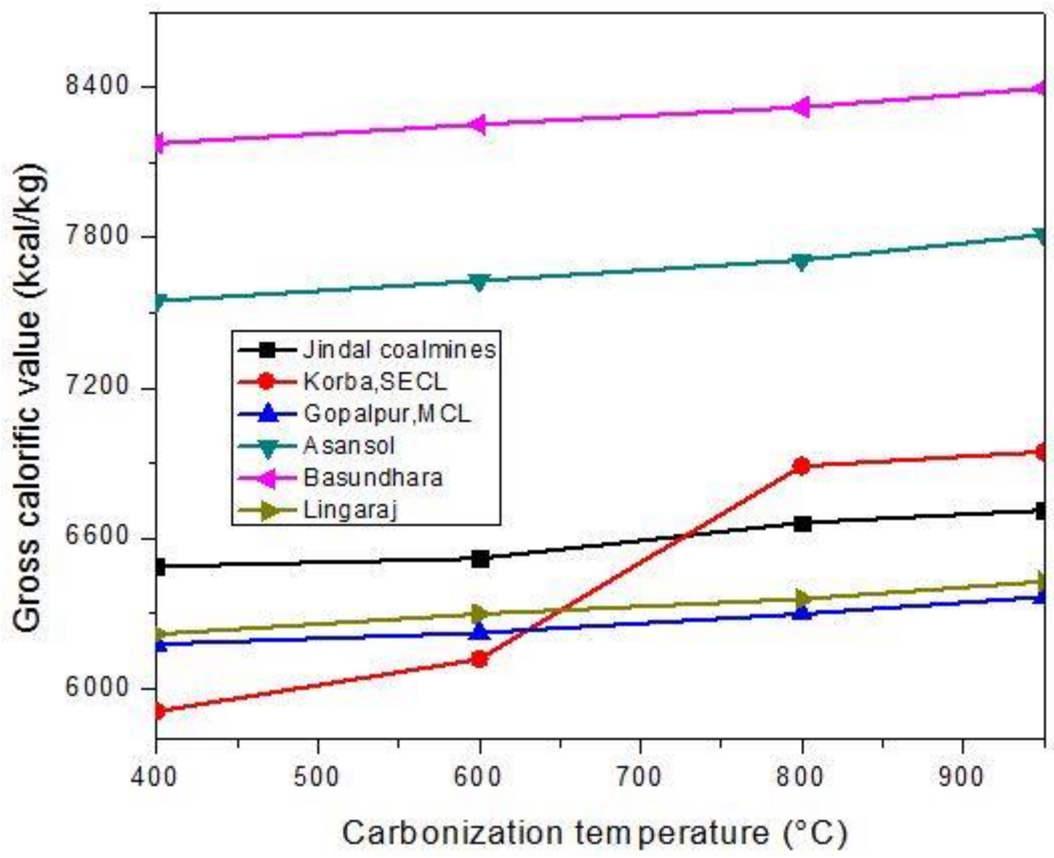


Fig 4.9: Variation in GCV of coal char due to rise in carbonization temperature

Gross Calorific values of the chars produced at 400,600,800 and 950°C have been shown in the Table 4.5 and graphically in Figure 4.9 , When carbonization temperature increase, gross calorific value also increases. This can be explained as, since the fixed carbon content rises with increasing carbonization temperature , calorific value or energy value also increases. However, this increase in calorific value is not much significant because ash content also rises simultaneously and found slight increment as shown in the graph.

4.6 Physical Properties of Coal Chars Produced

Table 4.6: Apparent porosity and density variation with rise in carbonization temperature (400 to 950℃)

Char produced from coal sample	Carbonization temperature (°C)	Apparent porosity (%)	Apparent density (gm/cc)
Jindal coal field	400	31	1.4
	600	28	1.5
	800	25	1.5
	950	22	1.6
Korba,SECL	400	38	1.3
	600	36	1.3
	800	35	1.4
	950	33	1.4
Gopalpur,MCL	400	43	1.2
	600	40	1.3
	800	37	1.3
	950	35	1.4
Asansol	400	34	1.4
	600	30	1.5
	800	27	1.5
	950	25	1.6
Basundhara	400	38	1.3
	600	35	1.4
	800	34	1.4
	950	31	1.5
Lingaraj	400	41	1.3
	600	38	1.3
	800	36	1.4
	950	34	1.5

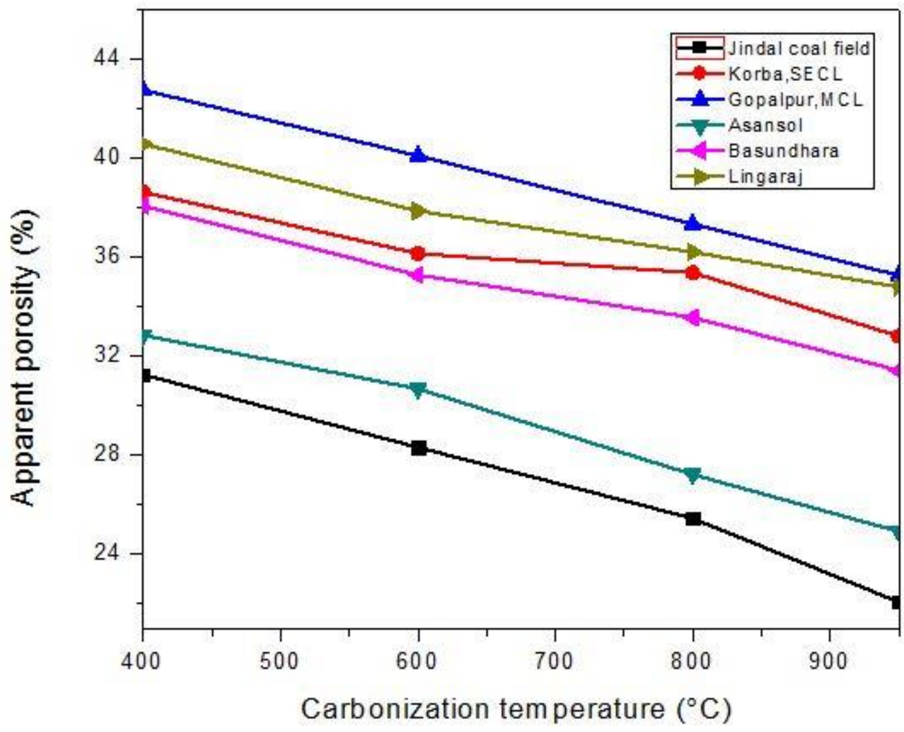


Fig 4.10; Apparent porosity variation with increasing carbonization temperature

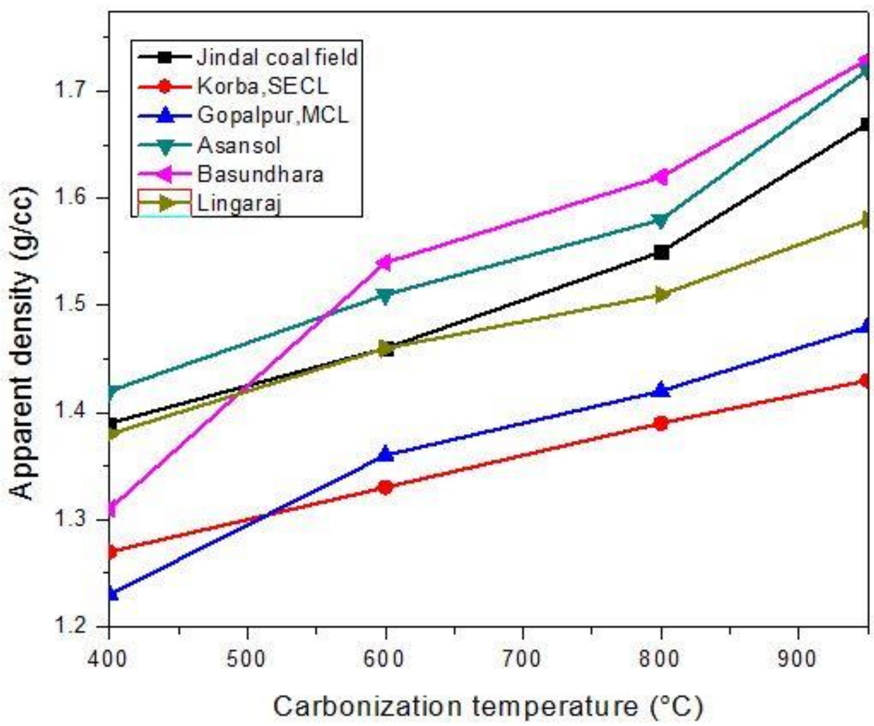


Fig 4.11; Apparent density variation with increasing carbonization temperature

Apparent porosity is related with vacancy or active sites present in the coal. As temperature increases carbon atom will diffuse to these vacant sites and hence the porosity will go down as the carbonization temperature increases as shown in the graph above (Fig 4.10).

Apparent density is the mass per unit volume, as the temperature rises the carbon content increase so the mass per unit volume will also increase. Therefore, apparent density increases with the rise in carbonization temperature. (Fig 4.11)

Porosity is concerned with char surface area, so when porosity increases, more surface area will be available to react with the gases like oxygen, carbon dioxide etc. resulting in higher reactivity. On the other hand, a decrease in porosity causes the reactivity to decrease. As the increase in carbonization temperature decreases the porosity, it will also decrease the reactivity of the coal char.

4.7 Ash Fusion Temperature of some Coal Ashes

Table 4.7: Ash Fusion Temperature of some of the coal sample ashes

coal ash sample	Ash fusion temperature (AFT) °C			
	Initial deformation temperature (IDT)	Softening temperature(ST)	Hemisphere temperature (HT)	Flow temperature (FT)
Jindal	1135	1318	1462	-
Asansol	1226	1296	1355	-
Basundhara	1208	1323	1496	-
Lingaraj	1128	1276	1378	-

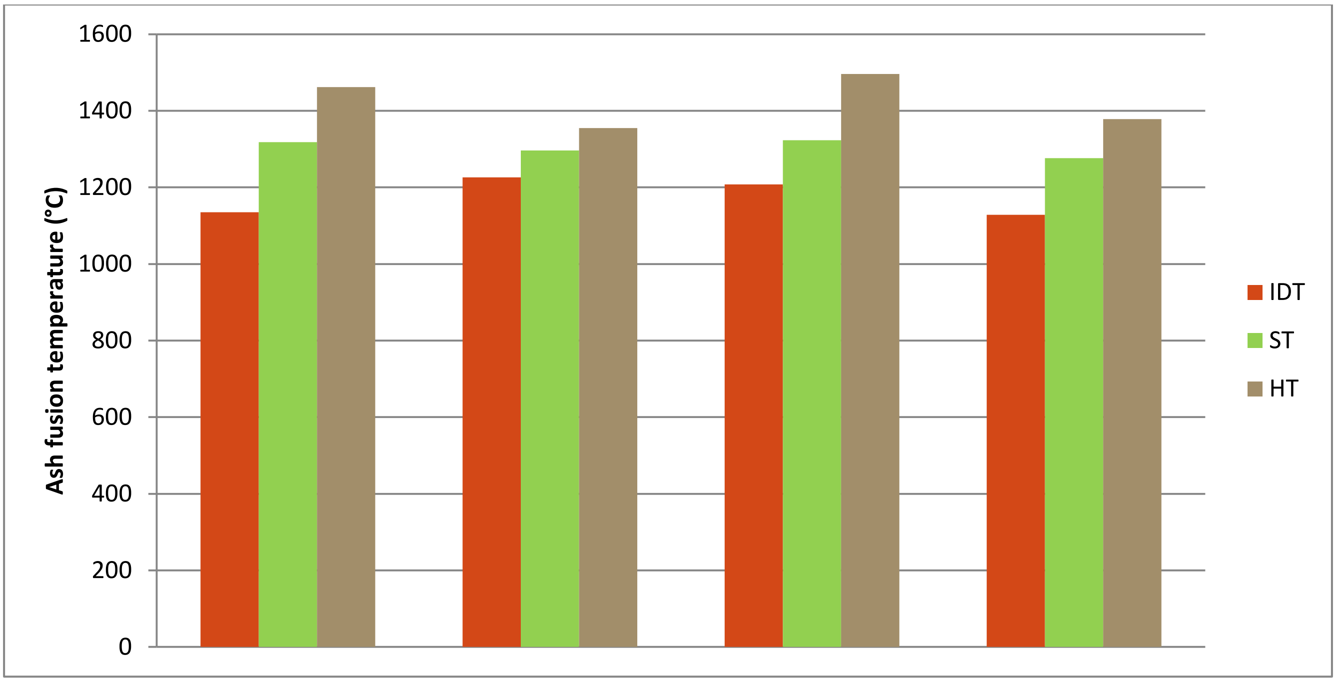


Fig 4.12: Ash fusion temperature of the some of the selected coal sample ashes in graph

In rotary kiln process, high ash fusion temperature is desired because low ash fusion cause prior liquefying of the coal ashes and adherence to the chars outward. Thus, it will lower the reactivity of the coal chars and lead to ring formation inward the furnace. To avoid so IDT should be sufficiently elevated (150°C) to working temperature of the furnace and ST should be greater than 1300°C.The results obtained from Ash fusion temperature analysis of some of the coal ashes have been enumerated in table 4.7 and represented graphically in fig 4.12.It is found from the result these coal ashes have sufficiently high initial deformation temperature . Flow temperature of these coal ashes could not be determined because FT occurred beyond temperature limit of the instrument.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

The following conclusions have been drawn based on the results obtained from the experiments performed on the coal and char samples:

1. From the Proximate analysis results it was found that most of the coals have high amount of fixed carbon (more than 40%). Coal sample obtained from Basundhara coal mines have highest fixed carbon content followed by Asansol, Jindal Gopalpur, Ligaraj and Korba mines respectively.
2. From the results of ultimate analysis of some of the coals it was found that they are having sufficiently high carbon and hydrogen content.
3. All selected coals except Basundhara and Asansol coals were found having nil value of caking index which is desired for using non-coking coals in industry.
4. Most of the coals were found having high calorific value (GCV > 6000 kcal/kg) which is the important property for the selection of coal in industry.
5. Effect of carbonization temperature on fixed carbon content of coals and chars was studied and it was found that with the rise in carbonization temperature (400 to 950°C) moisture and volatile matter content increases, on the opposite ash content and fixed carbon content increases.
6. As the rise in carbonization temperature results in fixed carbon content to increase, Calorific value was also found increasing with increase in carbonization temperature (400 to 950°C).
7. Rise in carbonization temperature has opposite effect on apparent porosity and apparent density. Apparent porosity decreases when carbonization temperature increases while apparent density increases with increase in carbonization temperature (400 to 950°C) .
8. Reactivity of chars towards CO2 was studied at temperature 950°C and the result was found suitable (>2gm/cc/sec) for sponge iron plant.
9. Most of the coal ashes were found having high fusion temperatures (IDT above 1300°C) which makes sure that there would not be any agglomeration problem inside the furnace.
10. On the basis of the results it was concluded that all the coals are suitable for sponge iron plants.

5.2 Suggestions for Further Studies

1) The characterization of physical and chemical properties of the coal samples performed for the current project can also be intimated for other coals from different parts of the country.

2) Investigation on microscopic properties of coal is also recommended

3) Investigation on strength of coal and char also need to be performed in forthcoming works.

4) Effect of carbonization temperature on the properties of coal char can also be extended for other parameters such as effect of heating rate and soaking time

CHAPTER 6

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